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# Focus issue introduction: synergy of structured light and structured materials

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**Abstract:** Structured light beams, such as optical vortices, vector beams, and non-diffracting beams, have been recently studied in a variety of fields, such as optical manipulations, optical telecommunications, nonlinear interactions, quantum physics, and ‘super resolution’ microscopy. Their unique physical properties, such as annular intensity profile, helical wavefront and orbital angular momentum, give rise to a plethora of new, fundamental light-matter interactions and device applications. Recent progress in nanostructured materials, including metamaterials and metasurfaces, opened new opportunities for structured light generation on the microscale that exceed the capabilities of bulk-optics approaches such as computer generated holography and diffractive optics. Furthermore, structured optical fields may interact with matters on the subwavelength scale to yield new physical effects, such as spin-orbital momentum coupling. This special issue of *Optics Express* focuses on the state-of-the-art fundamental research and emerging technologies and applications enabled by the interplay of “structured light” and “structured materials”.

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This special issue selects the state-of-the-art fundamental research and emerging technologies and applications enabled by the interplay of "structured light" and "structured materials".

Structured light beams, including optical vortices, vector beams, and non-diffracting beams, possess various unique properties. For example, optical vortices are associated by an annular intensity profile, a helical wavefront, and an orbital angular momentum. Tightly focused radially-polarized vector beams with a polarization singularity have been shown to produce a strong longitudinal electric field along the propagation direction, yielding a smaller far-field spot beyond the diffraction limit. Another class of peculiar structured light beams includes Bessel beams that are nondiffracting and self-healing, i.e. they maintain a narrow beam width over a long propagation distance and can reconstruct themselves behind obstacles in the course of their propagation. Finally, Airy beams and more generally accelerating beams constitute another family of beams that possess quasi-nondiffracting behavior. Structured light beams recently attracted significant attention in a variety of fields, such as optical trapping and manipulations, optical tweezers, sensing, space-division multiplexing optical telecommunications, nonlinear interactions, quantum physics, and 'super resolution' microscopy with a spatial resolution beyond the diffraction limit.

Going beyond foundational work on computer generated holography and diffractive optics, matter may now be designed and fabricated with subwavelength structure (e.g., metamaterials, metasurfaces) to transform optical fields. And conversely, structured optical fields may interact with matter structured on the subwavelength scale to yield new effects, e.g., spin-orbital momentum coupling or unconventional opto-mechanical effects for advanced optical manipulation. Furthermore, in recent years several demonstrations of structured light-matter interactions enabling the formation of various material structures, including chiral structures and laser-induced periodic surface structures, have been reported. Such advances in structured light transformation and generation enable miniaturized and

multi-functional (i.e. shaping wavefront, polarization state, etc.) optical components integrated on a chip.

The synergy between these two areas of modern optics, i.e. “structured light” and “structured materials” opens entirely new perspectives for fundamental and applied science.

This special issue received a total of 43-submissions. The topics of this special issue are listed below:

- Review of structured light and orbital angular momentum
- Structured light in anisotropic turbulence
- Material processing by structured light
- Metasurfaces for structured light generation
- Nonlinear singular optics
- Optical manipulation, and microscopy
- THz photonics
- Physical optics

We provide a short introduction for each paper and classify them into several categories as follows:

Orbital angular momentum 25 years on

This invited review article of orbital angular momentum is presented by Padgett in [1]. Since Allen et al. in 1992 established that light beams with helical phase-fronts carry an orbital angular momentum (OAM), it has been attracting much attention in a variety of fields, such as optical manipulation, imaging, quantum optics, optical communications and elsewhere. This review article addresses several research fields to date and considers new perspectives.

### **Structured light in anisotropic turbulence**

Structured light is expected to propagate through the air turbulence with less degradation than conventional light beams. Li et al. [2] establish the model to investigate oceanic turbulence effects on the received probability density and crosstalk of OAM modes. The authors show that anisotropic oceanic turbulence effects are smaller than those of isotropic oceanic turbulence under the same condition. Also, they point out the possibility to decrease the effects of turbulence on the received probability of OAM modes by tuning the wavelength and the transverse aperture of the Hermite-Gaussian vortex beam in the source's plane.

### **Integrated optics**

Peer et al. demonstrate the enhancement of absorption (or light emission) in solar cells (or organic light emitting diodes) enabled by light interaction with a periodically structured microlens array, which facilitates focusing of light on the nanoscale [3].

### **Material processing by structured light**

It was previously found that light beams with an OAM enable us to twist materials to establish helical structures. Masuda et al. for the first time demonstrate that even circularly polarized light with spin angular momentum (SAM) alone and without any OAM capable of twisting an azo-polymer film into a helical surface relief as an intermediate form [4]. Such helical surface relief further transforms to a non-helical bump-shaped relief with a central peak as a final form after an additional exposure.

Rapp et al. demonstrate ultra-high speed cleaving of crystalline materials by utilizing femtosecond Bessel laser beams [5]. Bessel beams enable the creation of homogeneous

cracks along the depth of the material. This technique is potentially applied to cleave sapphire with a spacing as high as 25  $\mu\text{m}$ .

In another paper, Syubaev et al. demonstrated chiral nanoneedles (nanojets) on silver and gold thin films resulting from illumination of the films with tightly focused nanosecond optical vortices [6]. Physical parameters of the chiral nanojets (height, aspect ratio etc.) were controlled by varying metal film thickness, supporting substrates, and the focused spot size of the optical vortices. They also suggest that interference of the incident and reflected optical vortices onto the films contributes mainly to establish such chiral nanojets.

Minowa and associates find that ZnO microspheres produced by laser ablation in superfluid helium contain bubble-like voids, even though they act as whispering gallery mode laser cavities [7]. The authors suggest that helium gas (or evaporated target material) contained in molten ZnO particles may create voids in the microspheres.

### Metasurfaces for structured light generation

Fan et al. propose a metasurface, composed of a single layer of amorphous titanium dioxide elliptical nanofins on the fused-silica substrate, to achieve high-efficiency generation of auto-focusing Airy beams [8]. Their numerical simulations suggest that such metasurface can be designed to tune the deflection and focusing length of Airy beam.

To date, the propagation of surface plasmon polaritons (SPP) around various surface defects and disorders has attracted a considerable attention owing to a significant potential for future applications. Shao et al. proposed a novel method to guide SPP through arbitrary distorted metal surfaces with slopes, bumps, and sharp corners is proposed [9]. The method will have potentially diverse applications to manipulate surface waves in integrated photonic circuits. In fact, several functional SPP devices, for instance, an adapter, a cloak, and a waveguide with a sharp bend, are demonstrated.

### Microscopy and optical manipulation

Structured light is poised to revolutionize modern microscopy. Turguet et al. demonstrate a nonlinear imaging of oriented GaAs nanowires by employing pump laser beam with binary phase modulation [10]. The proposed technique enables full control of the polarization in the focal volume resulting in significant enhancement of light-matter interactions.

Nanostructures, such as a plasmonic Bull's eye structure, provide functional add values, enhancement of fluorescence intensity, to the epi-fluorescence microscope. Tawa et al. successfully demonstrate the observation of extremely weak fluorescence signal from the 20 (40) nm size fluorescence nanospheres by utilizing a plasmonic Bull's eye [11].

Herne et al. aim at identifying the polarization state of the laser mode (ellipticity and orientation) in the trapping focus, and measuring the non-uniform circular rotation (rotation rates, orientation etc.) of calcite crystals in an elliptically polarized laser mode by synchronizing video images and a quadrant photodiode [12].

Optical tweezers based on optical radiation forces produced by a tightly focused laser beam are a powerful tool to trap sub-micron- or micron-size particles. However, they cannot efficiently manipulate nanoparticles. Mototsuji et al. demonstrate trapping of nanometer-sized dye aggregation by utilizing plasmon-resonant fields. In particular, it is shown that the J-aggregates can be easier trapped in comparison with the H-aggregates [13].

### Nonlinear singular optics

Structured media and structured light are likely to open a new direction in the domain of nonlinear optics.

Siwicki et al. propose a new approach for development of graded-index chalcogenide fibers [14]. Arbitrary refractive index gradients in chalcogenide glasses are obtained using core nanostructuring. The authors investigate nonlinear propagation in the designed

chalcogenide fiber aiming at achieving 3.5-8.5  $\mu\text{m}$  spectrum of coherent, pulse preserving supercontinuum.

Lutsky and Malomed introduce a model of the optical media with a spatially structured Kerr nonlinearity modulated by a set of singular peaks on top of a self-focusing or defocusing uniform background. They investigate the properties of solitons supported by such singular modulation [15].

### THz photonics

Focusing structured light with optical angular momentum beyond the diffraction limit is important but challenging task. Arikawa et.al. propose the tightly focusing technique of the structured light in a THz region by utilizing a circular array antenna [16]. Such tightly focused structured light enables quantum mechanical interaction between light and matter.

Liu et al. design a metamaterial built of a metal triangle pair connected by GaAs gap to produce hot spots for THz waves [17]. The authors suggest that an incident THz wave could be confined in the 1  $\mu\text{m}$  GaAs gap resulting in 100 times enhanced electric and magnetic THz fields.

### Physical optics

An “optical bottle” is a beam with a finite axial region of null intensity surrounded in all directions by light. Such beams find applications for trapping low index particles as well as for enhancing spatial resolution along the longitudinal direction in stimulated emission depletion (STED) fluorescence microscopy. Vella et.al. design the optimal birefringence distribution to convert a uniformly polarized input beam into the optical bottle with the sharpest possible axial null intensity [18].

Wei et al. experimentally demonstrate higher-order OAM modes through cascaded second harmonic generation in a 2-dimensional photonic crystal [19]. The proposed technique enables simultaneous generation of different OAMs with different colors.

Vector beams bring yet another degree of freedom for fundamental studies and applications of singular optics. Otte et al. aimed at developing a fundamental understanding of the properties of tightly focused higher-order singular vector beam by considering a spatially adjustable amount of radial and azimuthal polarization components [20].

Zamboni-Rached et.al. extend the scalar method of Frozen Wave based on superposition of Bessel beams to the vector one to provide exact solutions of Maxwell's equations for structured light of any polarization states (linear, azimuthal, and radial) over micrometer space regions [21].

Gutierrez-Cuevas et.al. also aim at establishing the model of tightly focused structured light using scalar and electromagnetic polynomials [22].

In another study, Ram and co-authors present experimental studies on diffraction of V-point singularities through equilateral and isosceles right triangular apertures [23], and demonstrate that diffraction collapses +1 (-1) index V-point singularity into two monstars / lemons (two stars).

Wang et al. report experimental and theoretical studies of vector structured light beams generated using a birefringent phase plate and a polarization demodulation module [24].

Finally, Liu et al. investigate Doppler effects arising from interaction of structured light and rotating structured targets [25]. In particular, the authors demonstrate that unlike the conventional rotational Doppler effect, the frequency shift is proportional to the variation of total angular momentum of light beam, regardless of the OAM of input beams.

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We hope that this special issue will encourage the readers to contribute to the exciting research field of structured light and structured materials.